Probing large scale structure with gravitational wave observations of binary black holes [arXiv:2005.01111]

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Introduction

Future gravitational-wave detectors will detect **hundreds of thousands of BBH events a year**. We can imagine these events as a *survey of BBHs*, akin to *galaxy surveys*.

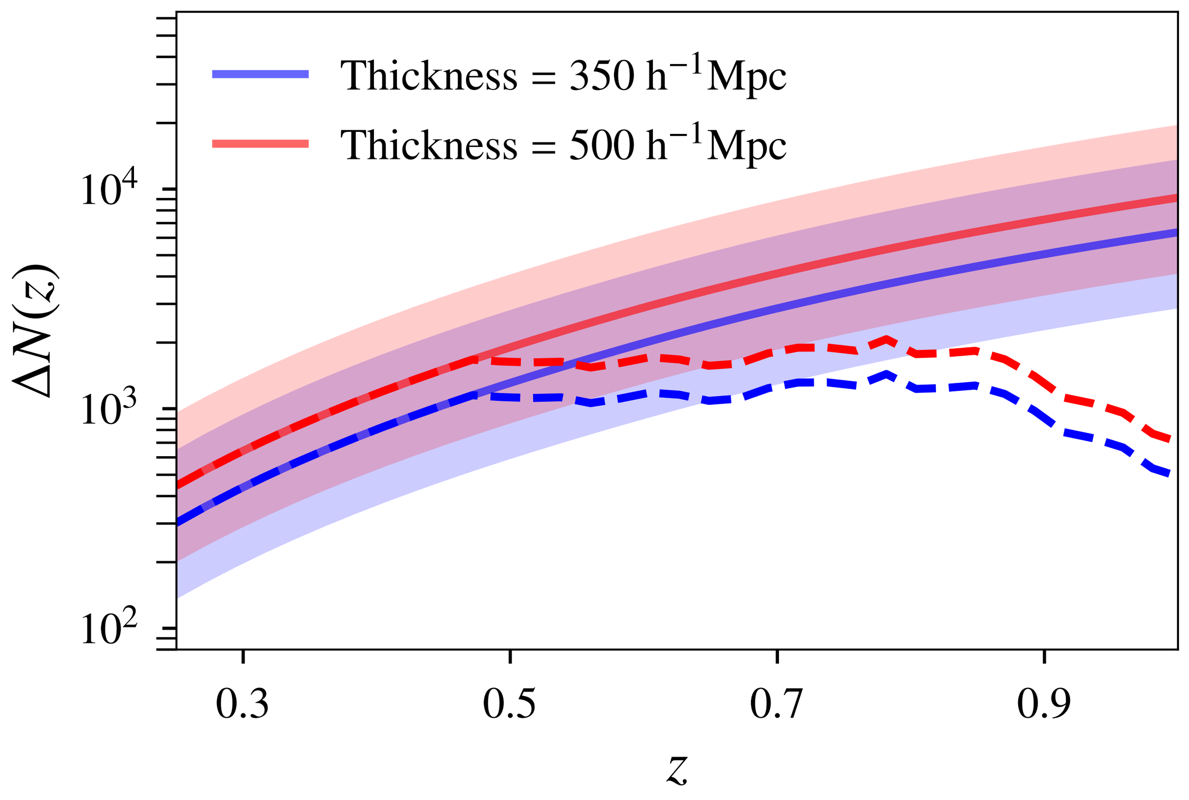

Figure 1: Solid curve with shaded region shows the total number of merger events as a function of redshift in shell of thickness $\sim 350\, h^{-1}$ Mpc and $\sim 500\, h^{-1}$ Mpc in comoving distance. The dashed lines show the average number of mergers in the shell of given thickness for which the errors in sky localization are within a degree square and errors in estimating the comoving distance are $\leq 90\, h^{-1}$ Mpc for a network of three 3G detectors.

Galaxy surveys can be used to measure the **two-point correlation function (2PCF)**. Given a cosmological density field $\rho(x)$, one can define overdensity field $\delta(x) := \rho(x)/\overline{\rho} - 1$. The 2PCF is then given by

$$\xi(r) = \langle \delta(\mathbf{x})\, \delta(\mathbf{y}) \rangle\,, \tag{1}$$

where angle brackets denote the ensemble average. Assuming standard ΛCDM cosmology, **we can calculate the 2PCF for dark matter ξ_{DM} theoretically**.

The Linear Bias Factor

Since dark matter is more abundant than the baryonic matter, the clustering of the galaxies is expected to trace that of the dark matter.

$$\xi_{\rm gal}(r) = b_{\rm gal}^2\, \xi_{\rm DM}(r), \tag{2}$$

$b_{\rm gal}$ is called the **linear bias** and depends on the luminosity and color type of galaxies. Similarly, we can also define a **bias which quantifies the clustering of the observed BBH population**:

$$\xi_{\rm BBH}(r) = b_{\rm BBH}^2\, \xi_{\rm DM}(r). \tag{3}$$

Localization errors and $\xi(r)$

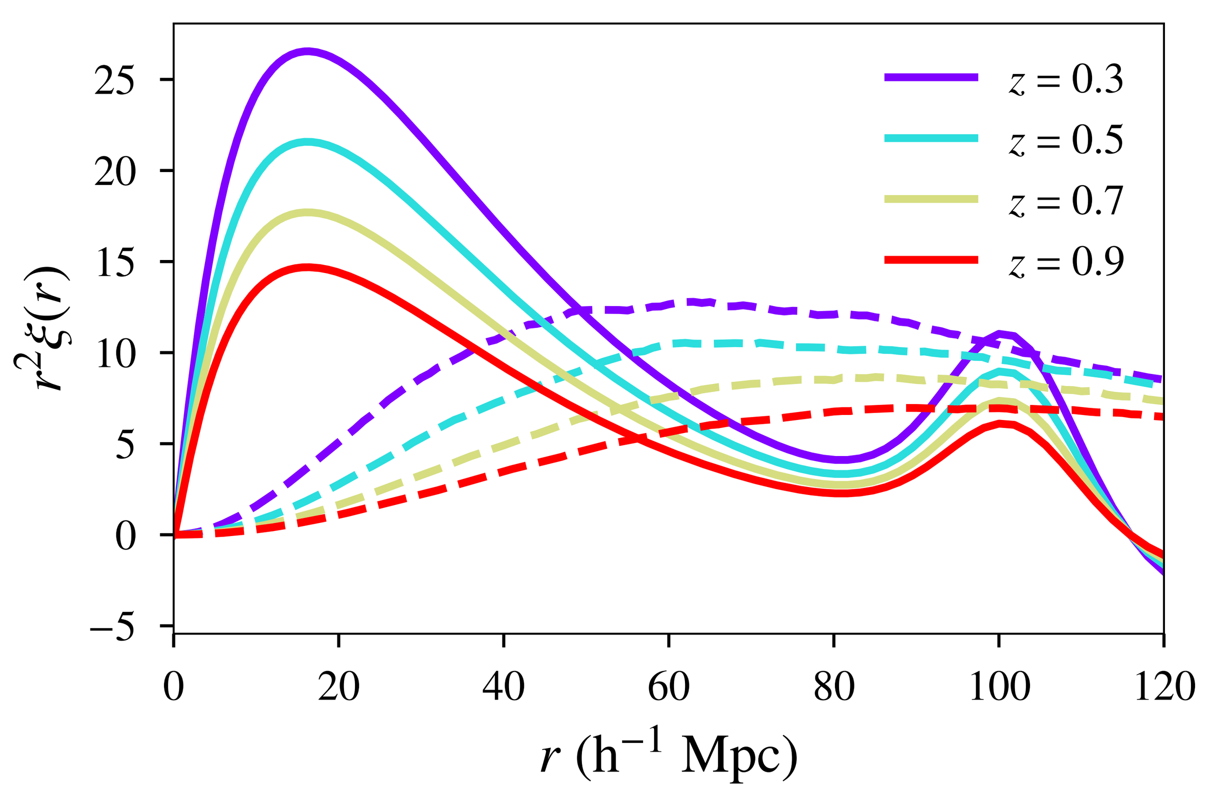

Figure 2: The "smeared" correlation function (dashed lines) and the "true" correlation function (solid lines) for various redshifts. The true correlation function is simply the dark matter correlation function assuming the standard model of cosmology. The "smearing" is calculated assuming that the distribution of errors in localization of GW population follow a Gaussian distribution with mean $\{\mu_{\rm RA} = 0.5°, \mu_{\rm dec} = 0.5°, \mu_{\rm d} = 50\, h^{-1}$ Mpc$\}$ and standard deviation $\{\sigma_{\rm RA} = 0.5°, \sigma_{\rm dec} = 0.5°, \sigma_{\rm d} = 20 h^{-1}$ Mpc$\}$.

Due to the large statistical uncertainties in the GW localization, **the observed correlation function of BBHs will smeared**. The smeared correlation function can be computed by convolving the actual correlation function with the localization posteriors obtained from GW data.

$$\xi(\mathbf{x}, \mathbf{y}) = \int_V dV_\mu \int_V dV_\nu\, P(\mathbf{x} - \boldsymbol{\mu})\, P(\mathbf{y} - \boldsymbol{\nu})\, \xi_{\rm tr}(\boldsymbol{\mu}, \boldsymbol{\nu}) \tag{4}$$

Simulations and Results

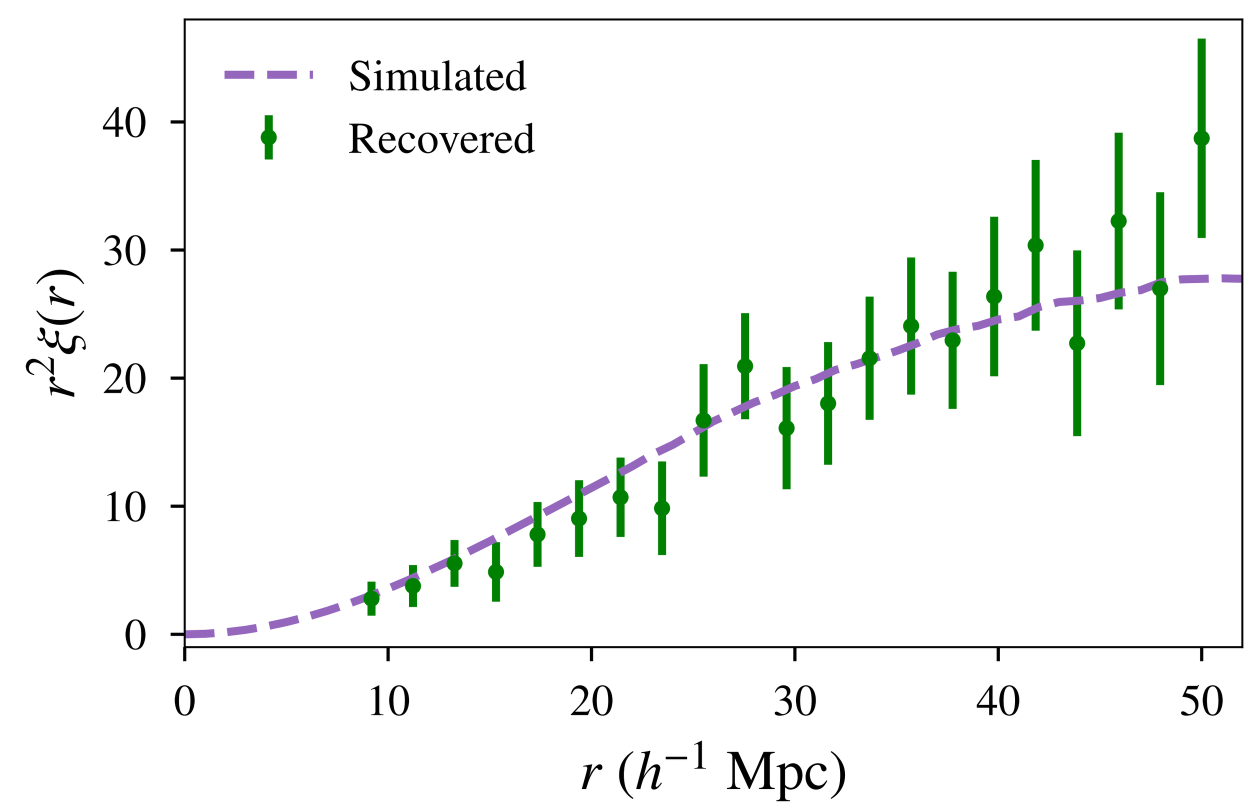

Figure 3: Smeared correlation function for a given distribution of localization errors is plotted along with the one recovered from simulated events at redshift 0.3 and input bias factor of 1.5. Smeared correlation function is scaled with input bias for comparison. We used 5000 simulated events distributed in a shell of thickness $350\, h^{-1}$ Mpc around redshift 0.3

We use the publicly available code LOGNORMAL_GALAXIES[1], to simulate galaxy catalogs at various redshifts with a certain bias $b_{\rm gal}$. We assume that GW events occur in any random subsample of the galaxies in the catalog, which essentially implies $b_{\rm BBH} = b_{\rm gal}$. We then simulate mock BBH catalogs by assuming a (gaussian) localization error distribution and check whether we are able to recover the bias consistent with the input value.

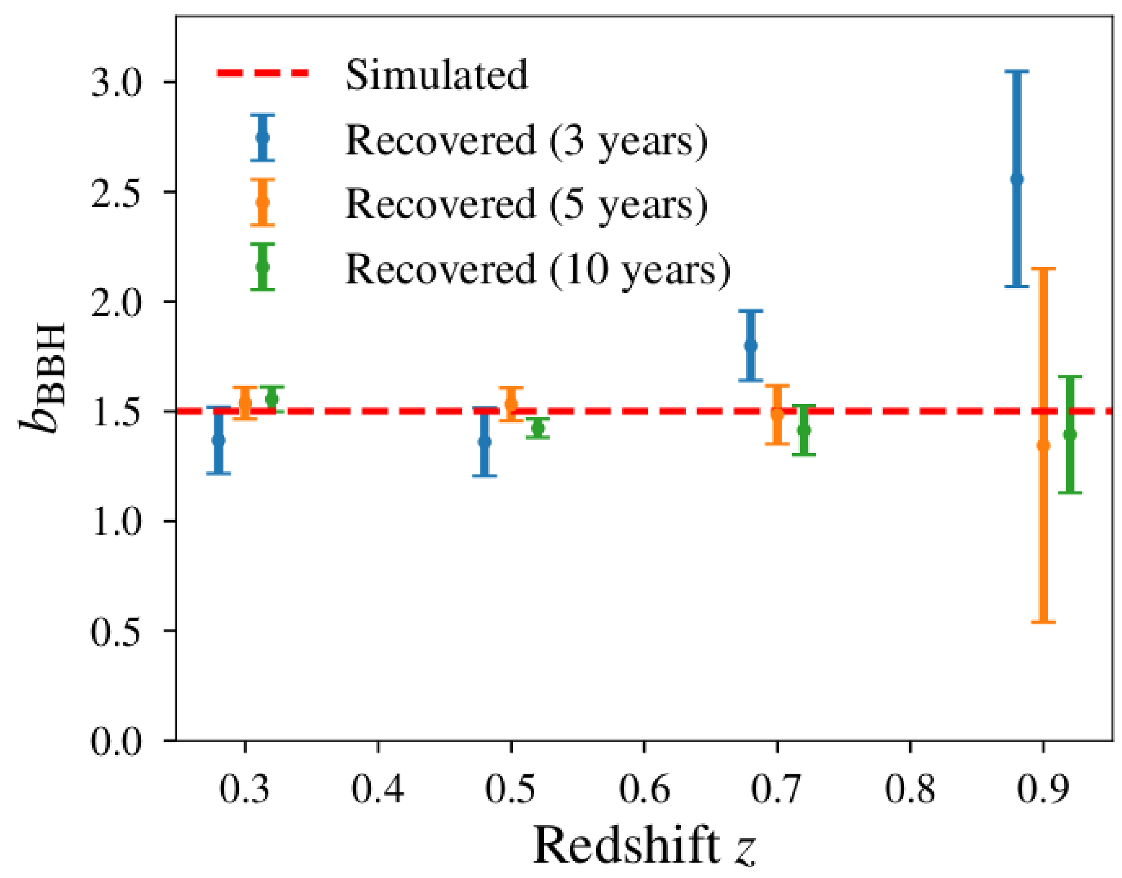

Figure 4: The recovered bias factor $b_{\rm BBH}$ (68% confidence regions) from various redshifts bins (with shell thickness of $\sim 350\, h^{-1}$ Mpc). The catalogs were created using the dark matter correlation function with linear bias 1.5. With a moderate observational time of three years, **we can recover the bias to within $\sim 20\%$ at $z \lesssim 0.7$, while errors in bias recovery are larger at redshift $z \sim 1$ due to large errors in localization**

The measured bias factor **probes the underlying dark matter distribution** using a novel astrophysical tracer and can be:

- compared to the clustering properties of the galaxies as measured from the optical surveys and obtain **insights on the type of galaxies that host these merger events**
- related to the **mass of dark matter halos these events reside in**
- used to to understand the **formation channels of the BBHs**.

[1] - https://bitbucket.org/komatsu5147/lognormal_galaxies/